

BUNBURRA ROCKHOLE: EXPLORING THE GEOLOGY OF A NEW DIFFERENTIATED BASALTIC ASTEROID. G.K. Benedix^{1,7}, P.A. Bland^{1,7}, J. M. Friedrich^{2,3}, D.W. Mittlefehldt⁴, M.E. Sanborn⁵, Q.-Z. Yin⁵, R.C. Greenwood⁶, I.A. Franchi⁶, A.W.R. Bevan⁷, M.C. Towner¹ and Grace C. Perotta². ¹Dept. Applied Geology, Curtin University, GPO Box U1987, Perth, WA, 6845 Australia (g.benedix@curtin.edu.au), ²Dept. Chem., Fordham University, 441 East Fordham Road, Bronx, NY 10458 USA, ³Dept. Earth & Planetary Sciences, American Museum of Natural History, New York, NY 10024, USA, ⁴NASA/Johnson Space Center, Houston, TX, USA, ⁵Dept. of Earth and Planetary Sciences, University of California at Davis, Davis, CA 95616, USA, ⁶Planetary & Space Sci., The Open University, Milton Keynes, MK7 6AA, UK, ⁷Western Australia Museum, Locked Bag 49, Welshpool, WA, 6986, Australia.

Introduction: Bunburra Rockhole (BR) is the first recovered meteorite of the Desert Fireball Network [1]. It was initially classified as a basaltic eucrite, based on texture, mineralogy, and mineral chemistry [2] but subsequent O isotopic analyses showed that BR's composition lies significantly far away from the HED group of meteorites (fig. 1) [1]. This suggested that BR was not a piece of the HED parent body (4 Vesta), but other explanations could also account for the observed oxygen signatures. Possible scenarios include contamination by components from other bodies (chondrites or other achondrites) or that 4 Vesta may not be as equilibrated as hypothesized [3].

After examining multiple pieces with different instruments (CT scans and x-ray maps), no obvious evidence of contamination was found. If BR is not from Vesta, a conundrum exists as no unusual features were found in mineral and bulk trace element chemistry [4] as exist for other anomalous basaltic achondrites such as Ibitira or Asuka 881394 [5,6]. These meteorites have distinct petrological and geochemical characteristics, in addition to their anomalous O isotope compositions, that set them apart from eucrites. Thus, early results provided a somewhat ambiguous picture of BR's petrogenesis and parentage. To clarify the nature of the relationship, if any, between BR and eucrites, we have performed a correlated stable isotope and bulk chemical study of several lithologic fragments.

Samples and Analytical Methods: Earlier O isotope [1] and bulk trace element studies [4] focused on analyzing the different lithologies characterized by different grain sizes to look at chemical variability. A 1.81g, slightly fusion-crust, piece of BR (measuring a little over 2 cm in long dimension) was allocated to the Open University for follow-up oxygen isotope analyses. The aliquots analysed here have a dominant grain size, but overall contained mixed lithologies. The main piece was divided into 4 smaller pieces (*labeled A, B, C, and D*), from which further fragments were taken. O isotopic compositions were measured on two fragments of piece A (*A and A/1*) and three fragments of piece C (*C/A/1, C/A/2, and C/B/3*). After O analysis, four powders (*A/1, C/A/1, C/A/2, C/B/3*) and two uncrushed (*A, B*) pieces were sent on to Fordham Uni-

versity for chemical analysis. Four of these were analysed for major and trace elements and two for trace elements only. Two of these subsamples (*A/1 and C/A/2*) were analysed at UC Davis to investigate the Cr isotopic systematics. Homogenized powders from the two chips were dissolved in Parr bombs for a 96 hour period at 200°C to insure complete dissolution of refractory minerals such as spinel. Cr separation was completed following the methods described in [7]. High-precision Cr isotope ratios were obtained using the Thermo *Triton-Plus* TIMS at UC Davis with the ⁵⁴Cr/⁵²Cr ratio expressed as ϵ -notation (parts per 10⁴) deviation from a terrestrial standard.

Oxygen isotope analysis was undertaken by laser fluorination using the methods described in [8]. System precision, as determined on an internal obsidian standard is: $\pm 0.05\%$ for $\delta^{17}\text{O}$; $\pm 0.09\%$ for $\delta^{18}\text{O}$; $\pm 0.02\%$ for $\Delta^{17}\text{O}$ (2σ). $\Delta^{17}\text{O}$ values were calculated using the linearized format of [9], with $\lambda = 0.5247$. All error values listed below are 2σ .

Bulk trace and major elements were analysed following the methods described in [10, 11] respectively.

Results and Discussion:

Stable isotopes The oxygen isotope compositions of 25 different fractions ($n = 42$) of BR are shown in Fig. 1. The mean $\Delta^{17}\text{O}$ of BR is $-0.127 \pm 0.044\%$ and the mean $\delta^{18}\text{O}$ is $3.98 \pm 0.22\%$ [12]. This is significantly different from the HED mean $\Delta^{17}\text{O}$ value of -0.246 ± 0.014 [3]. The five pieces for which bulk chemistry has also been determined have a much tighter mean $\Delta^{17}\text{O}$ of $-0.133 \pm 0.016\%$, at the upper end of the $\delta^{18}\text{O}$ range for BR ($4.09 \pm 0.16\%$).

The measured $\epsilon^{54}\text{Cr}$ for sample A/1 is -0.37 ± 0.11 and for C/A/2 is -0.35 ± 0.08 , identical within error. These values are resolvably different from the average $\epsilon^{54}\text{Cr}$ value range observed in eucrites of -0.7ϵ (Fig. 2).

The stable isotope systematics indicate that BR does not come from the same parent asteroid as eucrites. Interestingly, BR plots in the same field with Asuka 881394 [13] in the $\Delta^{17}\text{O}$ - $\epsilon^{54}\text{Cr}$ isotopes space – indicating they may be sampling the same differentiated body.

Bulk composition Like previous studies [3], BR appears similar in chemistry to eucrites. Bulk trace elements for all follow a volatility pattern (Fig. 3) very similar to basaltic and polymict, and distinct from cumulate, eucrites. Further, siderophile element contents in BR are low, at nearly the same level as in basaltic eucrites.

Bulk rare earth elements show a relatively flat pattern with a slight negative Eu anomaly for all samples, except piece C/B/3, which has a slight LREE enriched pattern without the Eu anomaly. Concentrations are 10-15xCI. The BR mode is dominated by plagioclase and thus the negative Eu anomaly may be evidence of earlier fractionation of a plagioclase rich component prior to formation of BR melts, similar to the case for lunar basalts.

The distinct O and Cr isotopes suggest that BR is sampling a different differentiated body to the HED parent body (4 Vesta). The bulk trace elements and low siderophile concentrations argue against contamination. BR is a jumble of lithologic fragments from a differentiated parent asteroid which may be the same body represented by Asuka 881394. This implies that they have been mixed on a fine scale, most likely by impact.

The next step is to determine the relationship between BR and A881394 and their possible parent body and to seek a better understanding of how trace element and isotope geochemistry co-varies with the observed variation in oxygen isotopic composition.

References: [1] Bland P. A., et al. (2009) *Science* 325, 1525–1527 [2] Weisberg M. K., et al. (2009) *Meteoritics and Planet. Sci.* 44, 429–462 [3] Greenwood et al. 2014 accepted EPSL. [4] Spivak-Birndorf L.J. et al. (2014) accepted *Meteoritics and Planet. Sci.* [5] Mittlefehldt D. (2005) *Meteoritics and Planet. Sci.* 40, 665–677. [6] Scott E. R. D., et al. (2009) *GCA* 73, 5835–5853. [7] Yamakawa et al. (2009) *Analytical Chem.* 81, 9787–9794 [8] Miller et al. (1999) *Rapid Comm. Mass Spec.* 13, 1211–1217. [9] Miller (2002) *GCA* 66, 1881–1889. [10] Friedrich J. M. et al. (2003) *GCA* 67, 2467–2479. [11] Wolf S. F. et al. (2012) *Talanta* 100, 276–281. [12] Benedix et al. (2013) Abstract#5142. *MetSoc* 76. [13] Sanborn M.E. et al. (2014) 45th LPSC. [14] Greenwood et al. (2005) *Nature* 435, 916–918. [15] Trinquier et al. (2008) *ApJ* 655, 1179–1185. [16] Mittlefehldt D. (2014) EPSL submitted.

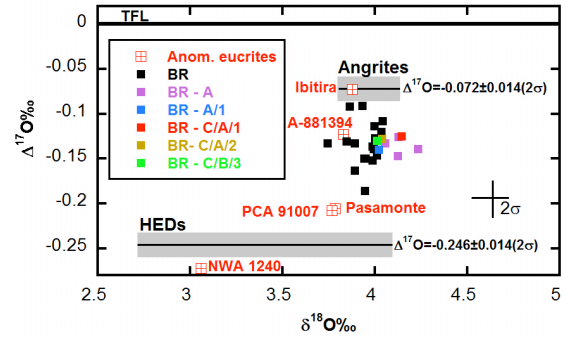


Fig. 1. $\Delta^{17}\text{O}$ vs $\delta^{18}\text{O}$ for BR. Also shown are the HED [4] and angrite fractionation lines [14]. The five pieces analysed for bulk composition in this study are shown in coloured symbols Grey boxes show the 2σ variation for the HED and angrite data [3,14]. Anomalous eucrite data from [6].

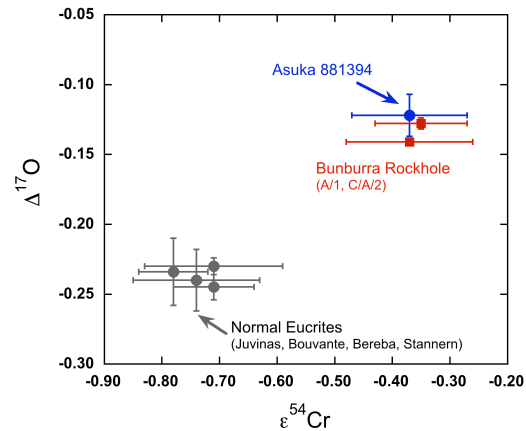


Fig. 2. $\Delta^{17}\text{O}$ vs $\epsilon^{54}\text{Cr}$ for BR (red symbols) and normal eucrites (green symbols). Data for eucrites from [15] and [7] for $\epsilon^{54}\text{Cr}$ and $\Delta^{17}\text{O}$, respectively.

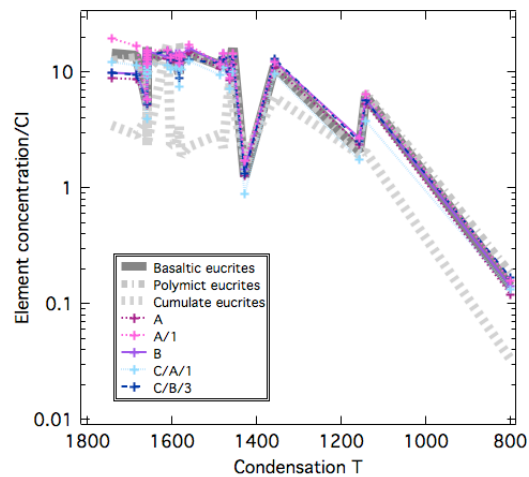


Fig. 3. Bulk trace lithophile elements (in order of increasing volatility) in different pieces of BR compared to average compositions for eucrites [data from 16].